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Design of Stilling Basins using Artificial Roughness

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ORIGINAL ARTICLE

ABSTRACT: Various types of hydraulic jumps have been analyzed experimentally, theoretically and numerically and the results are available in the literature. In this paper, very large series of experimental data are collected and used to develop a design equation for the optimal stilling basin with cube roughness elements. The experiments were conducted in a wide laboratory flume to study the effect of roughness parameters on the length of the roughened floor. Roughness elements are distributed in a staggered way. Two different heights of roughness were considered. The results of this study show the attractiveness of rough beds for energy dissipation below hydraulic structures. It was found that increasing the roughness length doesn't make great difference in energy loss, but the roughness height is very impressive at the hydraulic jump characteristics. Compared with the smooth bed, the rough beds decrease the relative the relative jump sequent depth by 5.3-12.76%. The axial velocity profiles at different sections in the jump were found to be similar, with some differences from the profile of the simple plane wall jet.

Key words: Hydraulic jump, Abrupt Drop, Rough beds

INTRODUCTION

Hydraulic jumps have been widely used for energy dissipation below hydraulic structures. In hydraulic jump-type energy dissipators, the jumps are often formed with the assistance of baffle blocks and are kept inside the stilling basin even when the tailwater depth is somewhat less than the sequent depth of the free jump (Peterka, 1958). A jump formed in a horizontal, wide rectangular channel with a smooth bed is often referred to as the classical hydraulic jump and has been studied extensively (Peterka, 1958; Rajaratnam 1967; McCorquodale 1986; Hager, 1992). If y_1 and v_1 are, respectively, the depth and mean velocity of the supercritical stream just upstream of the jump, with a Froude number of $Fr_1 = v_1 / \sqrt{gy_1}$ where g is the acceleration due to gravity, the subcritical sequent depth y_2^* is given by the well-known Belanger equation:

$$y_2^* / y_1 = 0.5(\sqrt{1+8Fr_1^2} - 1) \quad 1)$$

A preliminary investigation by Rajaratnam (1968) Indicated that, if the bed of the channel on which the jump is formed is rough, the tailwater depth y_2 required to form a jump could be appreciably smaller than the corresponding sequent depth y_2^*. For a relative roughness of the bed in terms of the supercritical depth y_1 equal to about 0.4, y_2 could be as small as $0.8y_2^*$, which is significant when it is realized that the tailwater depths required for Peterka's Basins II and III in terms of y_2^* are approximately 0.83 and 0.97, respectively. Further studies by Hughes and Flack (1984) and others (see Hager 1992) have supported this reduction in the required tailwater depth produced by the roughness of the bed. Further, Rajaratnam (1968) found that the jumps on rough beds were significantly shorter than the classical jump. But the main concern with jumps on rough beds is that the roughness elements located in the upstream part of the jumps might be subjected to cavitation and possible erosion, in which case the jumps would move downstream to the unprotected streambed, thereby causing erosion and possible damage to the structure itself. A recent study by Ead et al. (2000) of turbulent open channel flow in circular corrugated culverts indicated that the intense mixing induced by the corrugations produced significant Reynolds shear stresses in the plane of the crests of the corrugations and significant reduction in the velocity field above the corrugations. It appeared that, if jumps were made to occur on corrugated beds, significant reductions might occur in the required tailwater depth and length of the jumps. Further, if the crests of the corrugations were at the level of the upstream bed carrying the supercritical stream, the corrugations would not be protruding into the flow and hence may not be subjected to the same intensity of cavitation as in the case of protruding roughness. Hence, an exploratory laboratory investigation was performed with hydraulic jumps occurring on abrupt drop with rough beds and the results obtained are presented herein with the hope that this idea might be useful for energy dissipation for a range of hydraulic structures. During the past decades many studies have been reported the use of roughened bed stilling basin, but research has been done on the negative step with rough beds, therefore the aim of this study is the investigation of rough beds on the hydraulic jump properties at a negative steps. Izadjoo and Shafai Bejestan (2007), Shafai Bejestan and Neisi

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(2009). Since for abrupt jump of roughened bed basin no study can be found in the literature. A drop in stilling basins is used when the downstream depth is larger than the sequent depth for a classic jump in order to ensure the jump occurrence**.** Furthermore, the effectiveness of a drop in the stabilization of the hydraulic jump for a wide range of the downstream depth values has been widely established (Moore and Morgan, 1959). If the tailwater depth (y_2) is relatively large, the hydraulic jump is located in the upstream channel; this type of jump is called *A*-Jump (*Aj*). If the depth y_2 is reduced, the *Aj* is replaced by a wave that occurs at the drop. The supercritical stream is lifted up as a wave getting higher than the tailwater depth y_2; due to its own shape, this jump is called *Wave*-Jump (*Wj*). A further reduction of y_2 makes the *Wj* to turn into a *B*-Jump (*Bj*) with the toe located near the drop. The present study is concerned with the installation of cubic roughness with two height placed regularly (7-6-7 arrangement) on the bed, at an abrupt drop as shown in Fig. 1.

MATERIALS AND METHODS

Tests were carried out at the hydraulic laboratory of the Shahid Chamran University of Ahwaz. In order to reach to the main purpose of this study, a rectangular flume 80 cm wide, 70 cm deep and 15 m long were used. The side walls of the flume were made of plexy glass. Water was pumped from a storage tank to the head tank of the flume by a centrifugal pump. A cubed element made of hard plastic was installed on the flume bed (Fig.1) in such a way that the crests of the cubes were at the same level as the upstream bed. ($s=\Delta Z_0$). The supercritical flow was produced by a sluice gate. Water entered the flume under this sluice gate with a streamlined lip, thereby producing a uniform supercritical flow depth with a thickness of y_1. The heights of step were 3.5 and 4.5cm. Several types of jump at negative steps maybe occur with different tailwater depth. In order to establish the hydraulic jump in a specific location, the hydraulic jump should be controlled. It is performed by a gate. Therefore a gate (tailgate) at the exit end of the flume provided the control on the position of the jump. In all experiments, the gate (tailgate) was adjusted so that the jumps were formed B-jump (That this later is shown Bj®). The discharges were measured by an ultra sound flow meter installed in inlet pipe with DN=300mm. Values of y_1 and v_1 were selected to achieve a range of the Froude number, from 3.03 to 11.68. The Reynolds number $Re_1=v_1y_1/\upsilon$ was in the range of 81416-143191.

These tests were also performed for the flat bed.

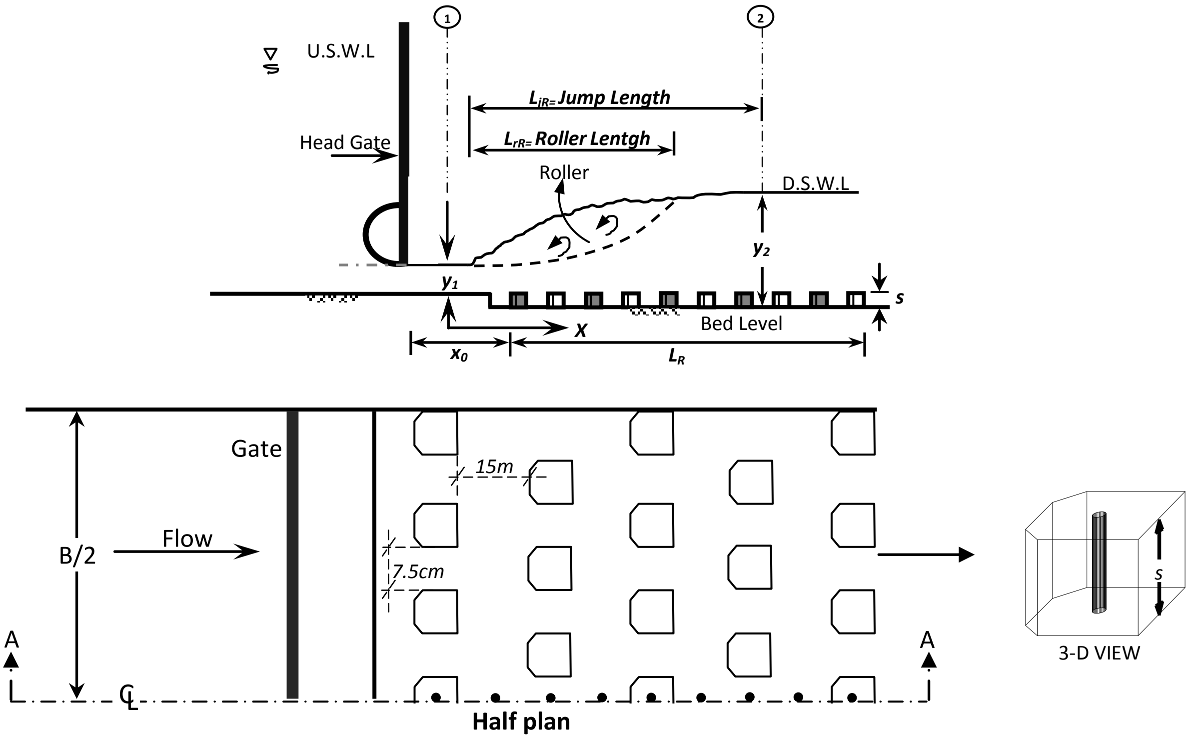

Figure 1. Definition Sketch

ANALYSIS OF DATA

Sequent Depth

The water surfaces were measured in the vertical center plane of the flume with a point gauge to an accuracy of 0.01 mm. These water surface profiles were used to determine the subcritical depth y_2 at the end of the jump, which was defined as the section beyond which the water surface was essentially horizontal, and the length of the jump *Lj*. Normalized water surface profiles are shown in Fig. 2 where $(y-y_1)/(y_2-y_1)$ is plotted against x/Lj, with y the depth of flow at any station x. Fig. 2 shows that water surface profiles are approximately similar and can be represented by one mean curve.

For Bj®, with a supercritical stream of depth y_1 and mean velocity v_1 , the depth at the end of the jump y_2 may be written as:

$$y_2 = f(Fr_1, \mathrm{Re}, s/y_1) \qquad 2)$$

For large values of the Reynolds number (involved in this study), viscous effects may be neglected and Eq. (2) reduces to:

$$y_2 = f(Fr_1, s/y_1) \qquad 3)$$

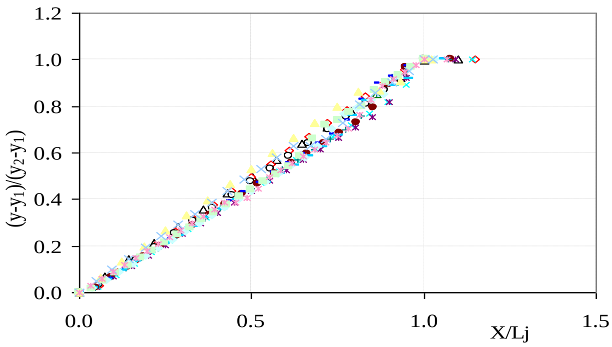

Figure. 2. normalized water surface profiles

The experimental results are shown in Fig. 3 with y_2/y_1 plotted against Fr_1 with the relative prolapse s/y_1 as the third parameter. Eq. (1) is also shown in Fig. 3. Fig. 3 shows that, when Froude number less than 5, the sequent depth (y_2) greater than the classics jump.

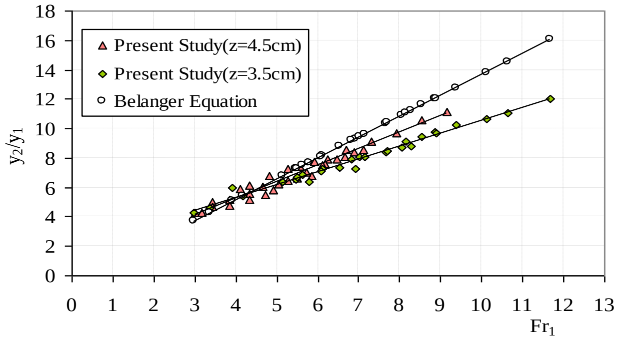

Figure. 3. Variation of depth ratio y_2/y_1 with Fr_1

In order to develop a general equation for the length of hydraulic jump under various roughness heights, several trials are attempted employing the multiple none linear regression analysis. About 80% of the collected experimental data are utilized to build the proposed regression in the light of equation 2. The rest of the observations are used to validate and to test the general equation. It was found empirically that:

$$y_2/y_1 = 0.895Fr_1 + 0.788(s/y_1) + 1.044 \qquad (4)$$
$$r^2 = 0.958$$

It is clear from the above equation the coefficient of s/y_1 is positive. This means that with increased height of roughness, sequent depth of hydraulic jump is increased. A comparison between the y_2/y_1 values measured in this investigation and those calculated by Eqs. (4) is plotted in Fig. 4.

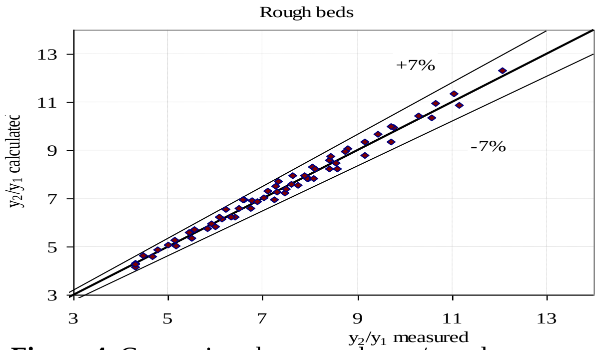

Figure 4. Comparison between the y_2/y_1 values measured in the present investigation and the ones calculated by Eqs. (4)

Eq. (4) has a mean error of 3.0% and 0 of the 62 ratios y_2/y_1 fall out of the error band of ±7%. Because the measurements of two different roughnesses were used, this result can be considered valuable.

Fig. 5 show typical velocity profiles of jumps at abrupt drop with rough beds for Fr_1=7.9 and y_1=3.5cm.

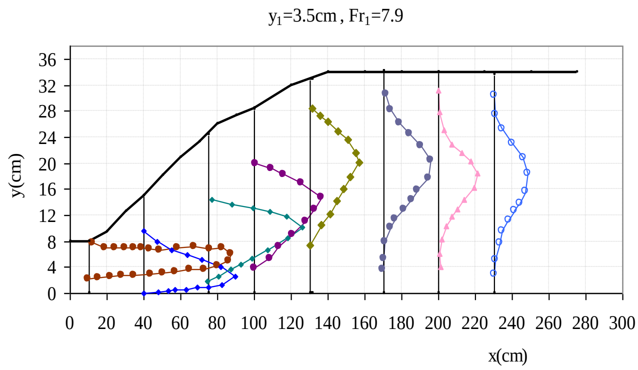

Figure. 5. Typical velocity profiles in Bj®

Having found that the velocity profiles in the forward flow are similar, it is necessary to study the variation of the velocity scale v_m and the length scales b and d with the longitudinal distance x. The velocity in the supercritical stream just before the jump, v_1, was varied from 1.75 to 5.93 m/s and at the last section of measurement the maximum velocity was in the range of 0.32-0.63 m/s. Figs. 6(a and b) show the variation of v_m/v_1 with x/Lj and x/y_1, respectively; the experimental observations show considerable scatter, thereby indicating that these length scales are not the correct ones.

Fig. 7 shows the variation of v_m/v_1 with x/L where L is the longitudinal distance at which v_m=0.5v_1. This length scale has been used before by Long et al. (1990) and by Wu and Rajaratnam (1995) for studying free and submerged jumps.

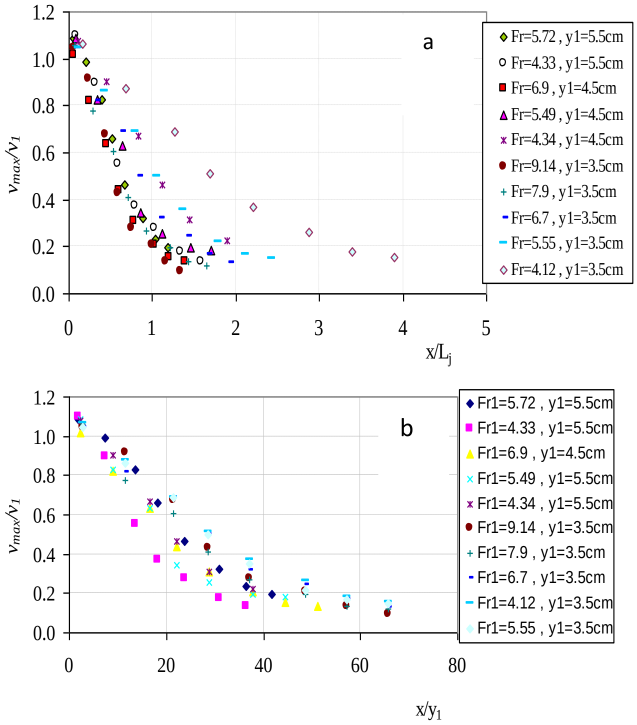

Figure. 6. Variation of maximum velocity vm /v1 with (a) x/Lj and (b) x/y1

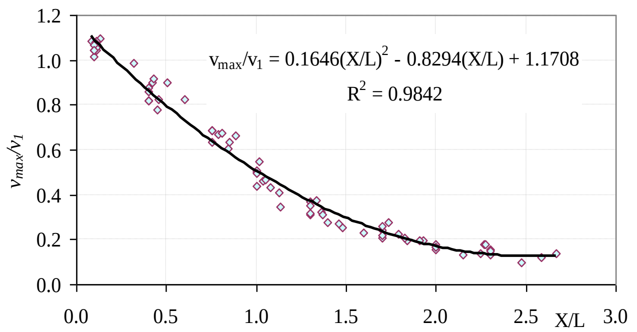

Figure. 7. Variation of maximum velocity v_m /v_1 with *x*/*L*

CONCLUSION

To improve the efficiency of the stilling basins, a new roughness shape was tested in the present study. It was found that increasing the roughness length doesn't make great difference in energy loss, but the roughness height is very impressive at the hydraulic jump characteristics. Compared with the smooth bed, the rough beds decrease the relative the relative jump sequent depth by 5.3-12.76%. The axial velocity profiles at different sections in the jump were found to be similar, with some differences from the profile of the simple plane wall jet. The maximum velocity v_m at any section in terms of the velocity v_1 of the supercritical stream was well correlated with the longitudinal distance x in terms of L, which is the distance where v_m=0.5v_1, and this relation was the same as that for jumps on smooth beds with the difference that L/y_1 was much smaller for Bj®.

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